Hurricane Science Tutorial

Kerry Emanuel
Lorenz Center, MIT
Why Should You Care?

Forecasting

- Much progress in social science of response to warnings, requests to evacuate, etc.

Forecasters are ambassadors to meteorology

- Opportunity to inform public
- Knowledge of hurricane science increases public interest and trust
Program

- Brief overview of hurricanes
- Current understanding
  - Basic state of the tropical atmosphere
  - Instability of the basic state – genesis
  - Energy cycle of mature hurricanes – concept of potential intensity
  - Negative influences on hurricanes
  - Statistics of hurricane intensification
  - Hurricane motion
  - Hurricanes and climate change
- Summary
Overview: What is a Hurricane?

**Formal definition:** A *tropical cyclone* with 1-min average winds at 10 m altitude in excess of 32 m/s (64 knots or 74 MPH) occurring over the North Atlantic or eastern North Pacific.

A *tropical cyclone* is a nearly symmetric, warm-core cyclone powered by wind-induced enthalpy fluxes from the sea surface.
Tracks of all tropical cyclones in the historical record from 1851 to 2010. The tracks are colored according to the maximum wind at 10 m altitude, on the scale at lower right.
Global Tropical Cyclone Frequency, 1980-2019

Data Sources: NOAA/TPC and NAVY/JTWC
Annual Cycle of Tropical Cyclones

Number of Events per Month

Northern Hemisphere (NH)

Southern Hemisphere (SH)
The spiral rainbands of Hurricane Floyd (left, 1999) versus the more compact Hurricane Andrew (right, 1992)
The Global Hurricane Hazard

- About 15,000 deaths per year since 1971
- $1.1 trillion 2015 U.S. dollars in damages ($21 billion/yr) since 1971
- Global population exposed to hurricane hazards has tripled since 1970

EM-DAT, 2020: The OFDA/CRED International Disaster Database
http://www.emdat.be/.
Global Normalized Damage from Tropical Cyclone Disasters

- 380% increase since 1970
- Population of TC-prone regions increased by ~200%
- Suggests that climate change has contributed to increasing damage

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- **Drowning (F)**: Fresh Water
- **Drowning (S)**: Salt Water
- **Wind**
- **Tornado**
- **Other**: Aircraft accidents, hypothermia, electrocution, ...

Total = 589

Source: Rappaport, E. N., 1999:
View of the eye of Hurricane Katrina on August 28th, 2005, as seen from a NOAA WP-3D hurricane reconnaissance aircraft.
Airborne Radar: Horizontal Map

360 km
(220 mi)
Hurricane Structure: Wind Speed

Azimuthal component of wind

< 115 ms$^{-1}$ - > 60 ms$^{-1}$
Specific entropy

EQUIVALENT POTENTIAL TEMPERATURE (K)

PRESSURE (MB)

RADIAL DISTANCE IN MILES FROM GEOMETRICAL CENTER OF EYE
Absolute angular momentum per unit mass

\[ M = rV + \Omega r^2 \]
Physics of Mature Hurricanes
Cross-section through a Hurricane & Energy Production

- Nearly isothermal expansion
- Isothermal compression
- Adiabatic expansion
- Adiabatic compression

- Height above ocean
- Ocean surface
- Radius (km)

- Ocean surface with low entropy

- Point A: Ocean surface with temperature $T = 27^\circ C = 300K$
Dependence on Sea Surface Temperature (SST):

Potential Intensity is not the same thing as SST!

Mean Slope = 8 ms\(^{-1}\)K\(^{-1}\) when \(U_{sfc}\) varied

Average dependence when radiation varied: 3 ms\(^{-1}\)K\(^{-1}\)
Why do real storms seldom reach their thermodynamic potential?

One Reason: Ocean Interaction
Strong Mixing of Upper Ocean
Comparing Fixed to Interactive SST:

Gert, 1999

Maximum surface wind speed (m/s)

September

No Ocean
Control
Figure 15. Loop and eddy currents in the Gulf of Mexico (image courtesy of Horizon Marine, Inc.).
A good simulation of Camille can only be obtained by assuming that it traveled right up the axis of the Loop Current:

Camille, 1969

- **Best-track**
- **Standard**
- **with Loop Current**
Wind Shear
Shear appears to weaken TCs by blowing dry, low theta_e air into the core.
Statistics of Hurricane Intensification

Common logarithms of the probability densities of open-ocean tropical cyclone intensity change rates in the North Atlantic region from 3504 observations (blue) and from 316,950 synthetic samples (red) of hurricane-intensity storms. Green lines or dots indicate the 5th and 95th percentiles of 1000 subsamples of the synthetic tracks data at the rate of the observed data for each intensity change bin. All distributions are bounded below by 10^{-2.5}. The synthetic data are subsampled every 6 h and rounded to 5 kt to match the best track data.
Tropical Cyclone Motion
Tropical cyclones move approximately with a suitably defined vertical vector average of the flow in which they are embedded.
Lagrangian chaos:
Vortices in interacting with Earth’s vorticity:
Hurricanes and Climate
Trends in Thermodynamic Potential for Hurricanes, 1980-2010
(NCAR/NCEP Reanalysis)
Inferences from Basic Theory:

- Potential intensity increases with global warming
- Incidence of high-intensity hurricanes should increase
- Increases in potential intensity should be faster in sub-tropics
- Hurricanes will produce substantially more rain: Clausius-Clapeyron yields ~7% increase in water vapor per 1°C warming
Summary

- Hurricanes are almost perfect Carnot heat engines, operating off the thermodynamic disequilibrium between the tropical ocean and atmosphere, made possible by the greenhouse effect.
• Most hurricanes are prevented from reaching their potential intensity by storm-induced ocean cooling and environmental wind shear

• Hurricanes move with some vertical average of the environmental flow plus effects due to the earth’s rotation and curvature, and to wind shear
• Hurricanes are expected to become more intense and rain more as the climate warms